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Estimation of Current From Near-Field Measurement

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Abstract—Knowledge of high-frequency currents in the chip and chip-package are necessary for EMI analysis and prediction, though measurement of these currents may be difficult to obtain in many cases. One possibility is to estimate currents from near-field scan data. In this paper, measurements were made of the magnetic field over a simple circuit and a chip package. The current flowing in the circuit and the chip lead frame was estimated from the compensated near-field data and compared with measurements made directly on the pins. Estimation was performed both with and without structural information of the lead frame. The susceptibility of estimated currents to measurement errors was analyzed. Results show this technique can be a powerful tool for analyzing high frequency chip currents.

Keywords—component; near-field scan; current estimation; scalar compensation; uncertainty, measurement

I. INTRODUCTION

Near-field scans are often used to indicate the orientation and intensity of the electromagnetic fields surrounding integrated circuits (IC) and printed circuit boards (PCB). A non-contact near-field measurement also provides a means to analyze the current distribution within the chip package. This information may be helpful in diagnosing the electromagnetic interference (EMI) problems created by sources in the chip [1, 2].

Once the current distribution over a chip package is located and quantified, the near or far fields, electric or magnetic fields can be easily calculated using geometry and load information. However, while the near- and far-fields are easy to measure, it may be difficult to accurately identify the EMI noise source. Current flowing within the chip package is critical for prediction of the EMI generated by the chip. These currents can be especially useful for EMI debugging.

The electromagnetic inverse problem has been widely used in many areas. For example, in electrocardiography the electrical potentials on the body surface are used to predict electrical activity of the heart [3, 4, 5]. Similar techniques may be used to predict electrical currents in the chip from near-field scan data.

In this paper, the inverse method described in the electrocardiography problem was used to estimate the current flowing within the chip package. Experiments were performed over a simple circuit and a chip lead frame, where currents could also be measured very accurately using conventional techniques. The estimated currents were verified using direct

measurements and a lumped element model. Problems of stability and susceptibility to measurement error are discussed.

II. ESTIMATION OF CURRENT

Currents flowing within the chip can be estimated in three basic steps. First, the magnetic field over a simple circuit and a chip package is measured and the measurements are compensated to correct for the influence of the probe on the measured fields. Second, the wire or trace geometry is used to define possible current paths. These paths are used to define the relationship between the unknown currents and the measured field using a Green's function. Finally, a standard linear least-square minimization of the sum-squared residuals is used to estimate the currents flowing in the circuit. These steps are discussed in detail in the following paragraphs in the context of a specific experimental setup and application.

A. Near Field Scan Setup and Field Compensation Method

For our experiments, the near magnetic field was measured using the a small loop probe shown in Fig. 1 and the near-field scan setup shown in Fig. 2. The size of the probe loop was about 0.7 mm^2 . The center of the loop was about 1.7 mm above the circuit during the measurement. The output of the probe was connected to a pre-amplifier with 25 dB gain using a 50-ohm coax cable. The characteristics of the amplifier and cable were calibrated using an HP8753d network analyzer. During scanning, the output of the pre-amplifier was connected to an oscilloscope through channel 2 using a 50-ohm coax cable. A dual-probe approach was used to synchronize the measurements made at different locations as described in [1], allowing an accurate measurement of phase. Based on this approach, a second loop probe was placed over the chip surface and used to generate a trigger signal.

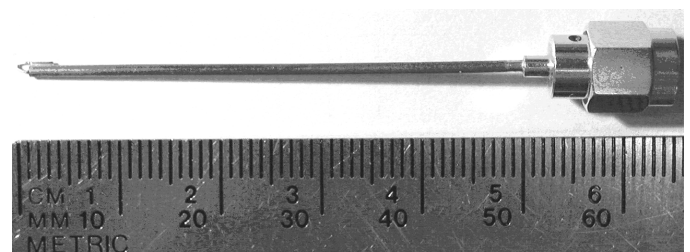


Figure 1. A photograph of a 1.5mm x 1mm magnetic field loop probe.

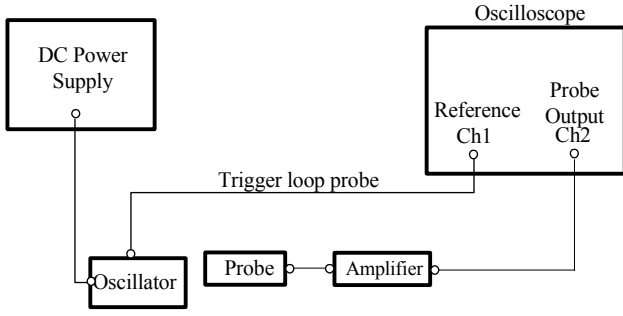


Figure 2. Setup for measuring near magnetic field.

B. Scalar Compensation

i Polarization, directivity and scattering are associated with the probe and influence the field measurement. A calibration and compensation procedure was described in [1] to remove these probe factors. In this paper, since the loop area of the probe was very small, a scalar compensation was used to find the amplitude of the magnetic field at the center of the loop as:

$$\vec{H} = \frac{V}{j2\pi f S \mu_0}, \quad (1)$$

where \vec{H} is the compensated magnetic field, V is the voltage measured by the oscilloscope, f is frequency, S is the area of the loop probe and μ_0 is the permeability of free space.

C. Defining current paths and developing relationship between current and measured field

Knowledge about the lead frame (the wire or trace geometry) may be used to define possible current paths. Since chip packages are typically electrically small structures, currents are constant along the trace. For some parts, for example the die area, it is not feasible to define possible current paths and a grid of current segments may be used to simulate the current density in that area as shown in Fig. 3.

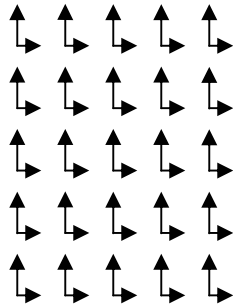


Figure 3. Inferred current network.

Once the possible current paths are defined, the relationship between the unknown currents in the defined paths and the measured field may be calculated using a Green's function. As the package is typically operating over a ground plane, both the current itself and its image should be taken into account. Consider a source area V' with current density $\vec{J}(\omega, x', y', z')$, where ω is angular frequency. Assume the current creates electromagnetic waves propagating in free space and the magnetic field at a plane z is $\vec{H}(\omega, x, y, z)$. Assume the area $z > z'$ is source free. The magnetic field in the source free area can be expressed as [7]

$$\begin{aligned} \vec{H}(\omega, x, y, z) &= \hat{x} \oint_{V'} [J_y(x', y', z')(z - z') - J_z(x', y', z')(y - y')] G_{12} dV' \\ &+ \hat{y} \oint_{V'} [J_z(x', y', z')(x - x') - J_x(x', y', z')(z - z')] G_{12} dV' \\ &+ \hat{z} \oint_{V'} [J_x(x', y', z')(y - y') - J_y(x', y', z')(x - x')] G_{12} dV' \end{aligned} \quad (2)$$

where

$$G_{12} = \frac{(1 + ikR) \exp(-ikR)}{4\pi R^3}, \quad (3)$$

$R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$ is the distance between a source point and field observation point, $\vec{r}' = x'\hat{x} + y'\hat{y} + z'\hat{z}$ represents the location of the source point, $\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$ represents the location of the field point, k is the wave number, and $\vec{J}(\omega, x', y', z') = J_x\hat{x} + J_y\hat{y} + J_z\hat{z}$ is the current source in source area V' .

D. Estimating unknown currents

Equations (2) and (3) can be used to find a relationship between currents and the measured magnetic field as:

$$TJ = H, \quad (4)$$

where H is the measured magnetic field after compensation with the method describing at step B, J is a vector giving the magnitude of (unknown) current sources defined in step C, and T is a transfer matrix between these currents and the magnetic field over the measurement plane as defined by equations (2) and (3). A standard linear least-square minimization of the sum-squared residuals may be used to solve for the currents as:

$$J = [T^T T]^{-1} T^T H. \quad (5)$$

III. CURRENT ESTIMATION OVER A SIMPLE CIRCUIT

The ability to estimate currents was first tested in a simple circuit, shown in Fig's 4 and 5. The circuit consists of a source feeding two loads (50 and 100 ohms) through wires suspended 2.5 mm over a ground plane. A 100 MHz crystal oscillator was

used as the signal source. The distance between the center of the circuit (where the wires are joined) and the source or the load is 1 cm. The angle between the wires feeding the 100-ohm load and 50-ohm load is about 17 degrees.

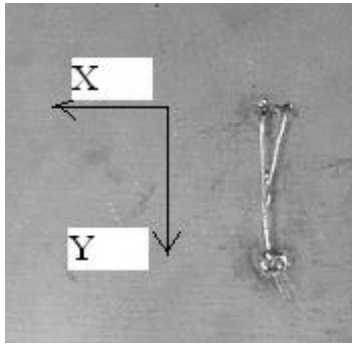


Figure 4. Photo of circuit.

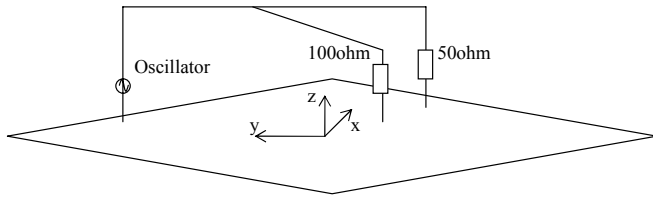


Figure 5. Definition of experimental setup.

The magnetic field over the circuit was scanned over a 2 cm (y direction) by 1 cm (x direction) area using a 49 by 25 grid of sample points. The output of the probe was connected to a Tektronix TDS 520A oscilloscope. The measured time domain signal was transformed into the frequency domain using the Fast Fourier Transform (FFT). Fig. 6 shows the compensated magnetic field measured at 100 MHz. The phase is required to recover the time domain waveform. Note that while the general location and magnitude of currents is distinguishable in the measured magnetic field, details are well hidden. Our measurements also found significant magnetic field components at harmonics of 100 MHz. Generally, these harmonics extended to 1 GHz. Those harmonics with frequency above 1 GHz were negligible.

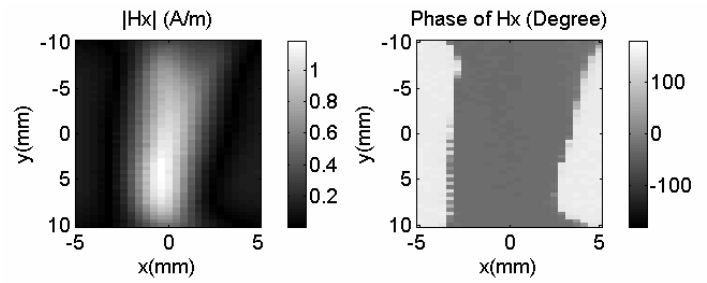


Figure 6. Compensated magnetic field.

A. Estimation of current using trace geometry

To estimate currents within the wires, the wire or trace geometry was used to define possible current paths. Since the circuit is an electrically small structure, current flowing through the traces is constant along the trace. The only unknowns are the current flowing through the trace to the 50-ohm resistor, through the trace to the 100-ohm resistor, and the current flowing from the source.

The current in the traces was estimated at the oscillator's frequency of 100 MHz and its harmonics up to 1 GHz. To verify the result, the voltage across the 50-ohm resistor and 100-ohm resistor was measured using a 25 to 1 probe and the currents flowing in these resistors were calculated from this measurement using Ohm's law, assuming parasitics to be negligible. Fig. 7 shows the current distribution at 100 MHz calculated from the voltage measurement using Ohm's law and the current estimated from the near-field scan. The figures are nearly indistinguishable.

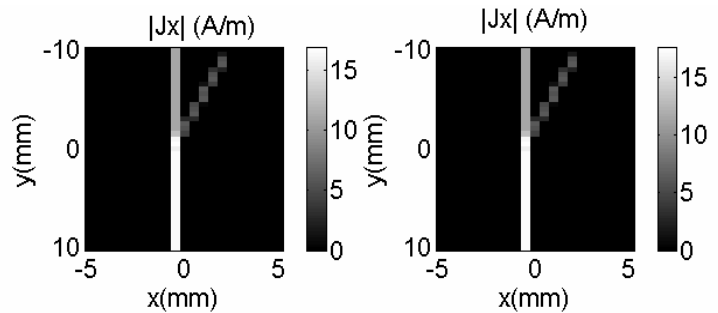


Figure 7. Calculated and estimated current using trace geometry at 100 MHz.

After the current was estimated at several frequencies, the time domain current was recovered by inverse FFT. Fig. 8 and Fig. 9 show the current flowing in the 50-ohm and 100-ohm resistor. The dashed curve was estimated from the magnetic field measurement and the solid curve was calculated from the voltage measurement. Maximum errors were less than 2 mA over an approximate 25 mA range.

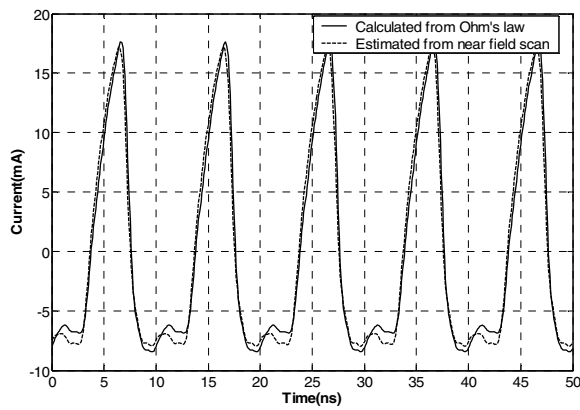


Figure 8. Estimated current in time domain (100-ohm load).

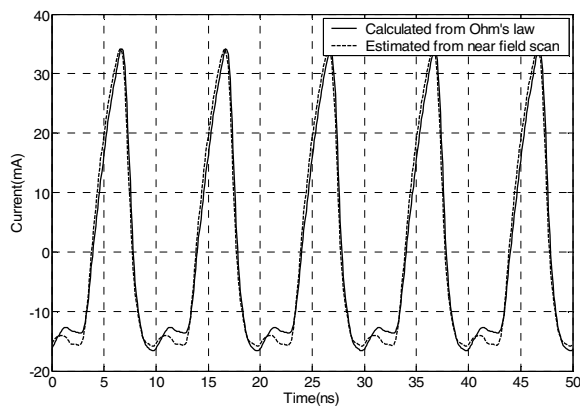


Figure 9. Estimated current in time domain (50-ohm load).

B. Estimation of current without structure information

Information about possible current paths helps to constrain the solution set and thus yields better current estimates. To show that currents could be estimated without structural information, however, currents were estimated again without using current path geometry. The current within the circuit was estimated from a 21 by 11 network of current segments, as shown in Fig. 3. Fig. 10 shows the estimated current distribution using this assumption. While estimates are not as good as in Fig. 7, more detail is clearly available than from only the near-magnetic field scan, without processing, in Fig. 6.

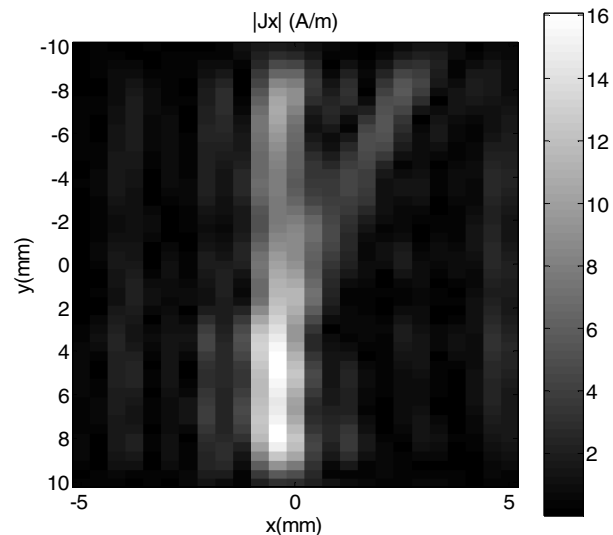


Figure 10. Estimated current from near-field scan.

IV. ESTIMATION OF CURRENT OVER A CHIP LEAD FRAME

Currents within a chip lead frame were also estimated from near magnetic field scans. Fig. 11 shows a photo of the experimental setup and the source and load definitions. The chip lead frame was held 3 mm above a solid return plane. The silicon die was replaced by a piece of copper tape so that all the leads were shorted to one other at the typical location of the chip. The lead frame was fed through a 50 ohm source through two pins on one side of the chip. Currents returned through 3 pins terminated to the ground plane through 75 and 50 ohm loads on the other side of the chip, as shown in Fig. 11. The ends of all other pins were left floating.

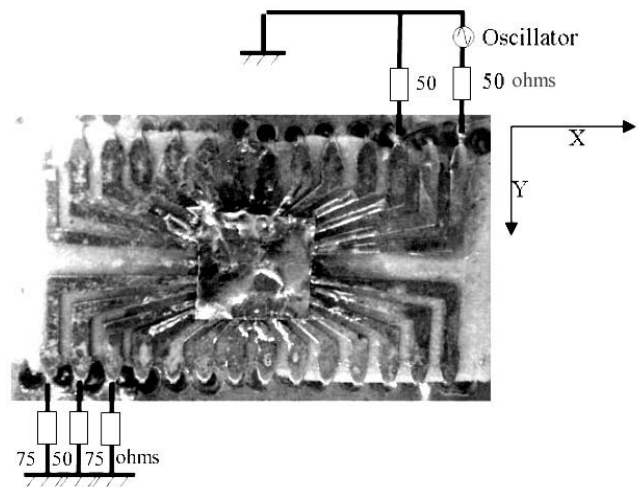


Figure 11. Photo of a chip lead frame.

To simplify the measurement procedure, near-field measurements were performed using a network analyzer. Port 1 of the network analyzer was connected to the feed pins of the chip and used as the signal source; Port 2 was connected to the probe output. There were no synchronization problems with

this measurement because the network analyzer automatically synchronizes port 1 and port 2.

The near-field scan was made over a 2 cm (y direction) by 4 cm (x direction) area (101 by 141 points). Fig. 12 shows the compensated magnetic field measurements at 100 MHz.

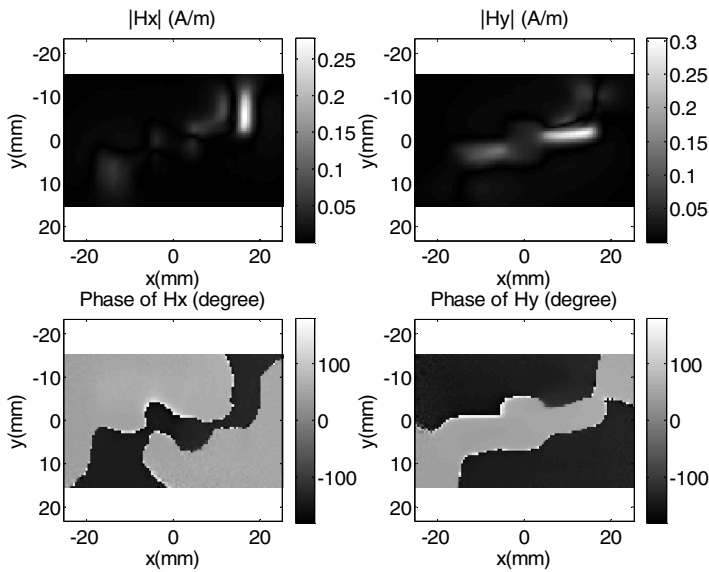


Figure 12. Compensated magnetic field.

The lead frame trace geometry was used to define possible current paths. There were a total of 28 traces in the lead frame; the magnitude of the current flowing in each trace was unknown, though the path was well defined. For the copper patch in the center of the lead frame, however, the current paths were not well defined. The 10 mm by 10 mm patch was divided into 25 small patches. The area of each patch was 2 mm by 2 mm. Two unknowns were associated with each patch, one for J_x (the current in the x-direction), and one for J_y (the current in the y-direction), similar to the current segment distribution shown in Fig. 3. There were 78 unknowns total.

Fig. 13 shows the current distribution in the package leads as calculated from Ohm's law. Typically, the inductance associated with these traces is around 10 nH, which can be ignored at 100 MHz compared with the impedance of the 50-ohm or 75-ohm resistors. Fig. 14 shows the current distribution at 100 MHz estimated from the near-field scan measurement. The recovered current shown in Fig. 14 does not perfectly match the currents calculated in Fig. 13 but is close. The primary difference are some weak signals estimated in traces that have an open load. There are several possible explanations for this phenomenon:

- The possible trace currents and their image are both considered in this model, however, the multiple reflections between the lead frame and the ground plane are not considered. The failure to include these reflections in the calculation of the transfer matrix may cause errors in the estimated currents.
- The model does not account for capacitive coupling.

- The calibration and scalar compensation of the probe may not be sufficient for the purpose of estimating currents.
- The location and rotation of the probe with respect to the chip lead frame were determined manually and may be in error. These errors in geometry may lead to errors in estimated currents, as shown in the following section.
- Random noise in measurements may cause additional errors in estimated currents.

V. UNCERTAINTY IN CURRENT ESTIMATES

As mentioned in the previous list, the accuracy of estimated currents is dependent on the accuracy of assumptions and measurements. Errors in the position of the probe relative to the device under test, errors in the rotational orientation of the probe, and random noise in the measured fields will create uncertainty in the estimates of current. To show the effect of these errors, currents were estimated when there were errors in probe position and orientation and when noise was added to measured fields. The error in estimated currents was then quantified as:

$$Error = \frac{\sum |estimated_current - true_current|}{\sum |true_current|}. \quad (5)$$

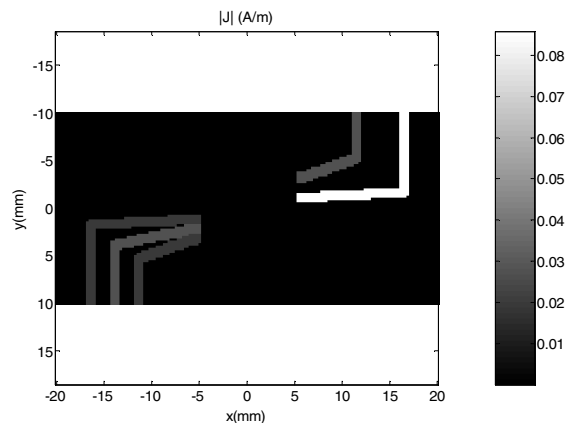


Figure 13. Current estimated using Ohm's law.

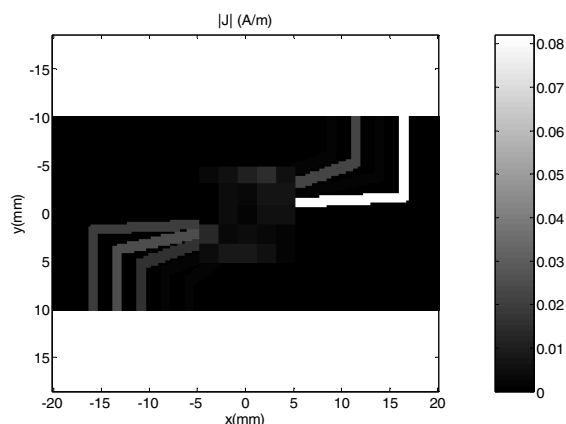


Figure 14. Current estimated from near-field scan.

A. Horizontal or vertical position shift

As the probe scan area is set manually by eye, there may be a small error in the assumed probe position relative to the chip package. For example, we may think the probe is on top of a trace, but actually it is 0.5 mm to the left of that trace. To show the effect of such an error, the current flowing through the lead frame was assumed to have a value as shown in Fig. 14. Then, the magnetic field 1.7 mm above the surface was calculated from these currents. The calculated magnetic field was then shifted 0.5 mm in the x direction and the current distribution was estimated from this shifted magnetic field. The error in the inferred currents was 12.4%.

B. Rotation of probe

The loop's orientation relative to the chip is also set by eye and subject to error. For example, we may think the loop is perpendicular to the x axis when it is actually oriented at 85 degrees with respect to the x axis. To show the effect of such an error, the current flowing within the chip was assumed to be as shown in Fig. 14. The magnetic field 1.7 mm above the surface was calculated from these currents. The field measured by the loop probe was then calculated when assuming the orientation of the probe face (normal direction) was at 15 degrees with respect to the x axis when measuring the magnetic field in the x direction. Thus, the measured field should be a combination of the magnetic field in x and y directions rather than just the x direction. The current distribution in the lead frame was then estimated from these erroneous measurements. The error in the estimated currents was 18.0%.

C. Random noise

Random noise was also added to the simulated field to test the susceptibility of the estimated currents to these

measurement errors. For our test, the average amplitude of the noise was set at 20% of the highest signal level. For 20% noise added to measured fields, the error in the estimated currents was 21.8%.

VI. DISCUSSION AND CONCLUSIONS

A procedure to estimate high-frequency currents from near magnetic field scans was described and applied to two examples, one a three wires circuit, and the other a chip lead frame. Generally, the estimated currents were accurate if the possible current paths (trace geometry) was well defined. Without constraining current paths, it was possible to get a better idea of current magnitudes and paths than through manual analysis of near-field scans themselves, though the precise magnitudes and paths were difficult to discern. Structural information is required for good estimates of currents. The better this information is known, the better the estimates. Here, structural information was obtained by removing the plastic packaging material with a DREMEL tool, though structural information may also be available from the chip manufacturer. In our experiments, for errors that might be expected in an experimental setup, errors in the position and orientation of the probe and additive noise result in approximately 20% (1.6 dB) errors in estimated currents.

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